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A Simplified Approach for the Annual and Spatial Evaluation of the Comfort Classes of Daylight Glare Using Vertical Illuminances

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Abstract: A simplified approach to calculate the daylight glare comfort class (imperceptible, perceptible, disturbing, or intolerable glare) on annual basis and for a grid of points in a space is presented. This method relies on the calculation of the vertical illuminance (E_v) for each grid point only, which is compared to an E_v threshold value for each daylight glare comfort class. These E_v threshold values are determined through a comparison with the Daylight Glare Probability (DGP) values on an annual basis through a fault-detection technique, for a reduced number of points. Compared to an annual calculation of exact DGP values on a certain grid, this approach is able to evaluate the daylight glare comfort classes only, but it is less time consuming. The paper presents and critically discusses this simplified method by means of its application to different case-studies: south and west oriented office in Turin (Lat 45.1° N), in which the DGP is assessed for three points in the space, considering glazing with different transmission properties (specular or scattering) and visible transmittances, as well as three operable internal shading systems (one venetian blinds and two roller blinds, for solar or glare control). For the presented case studies, the average error in the classification of the space according to daylight glare comfort classes is below 5% when comparing this simplified approach to related DGP values.

Keywords: daylight glare comfort classes; glare spatial assessment; annual daylight simulation; simplified glare evaluation; fault-detection analysis; eye vertical illuminance; daylight glare assessment

1. Introduction

The topic of daylighting has always been crucial in the design process of a building, both as far as the related energy demand for lighting is concerned and for its key role in determining the indoor environmental quality perceived by the occupants of a space. Daylighting shows to have a significant influence on the comfort level of the occupants, in terms both of visual comfort and non-visual effects [1–6].

Focusing on daylight visual comfort, this is a complex phenomenon influenced by several lighting aspects, including the illuminance on task surfaces and the glare related to daylight sources. These are commonly taken into account during the design phases with objective parameters, including: the horizontal illuminance on the workplane, which is the quantity most commonly used to assess the lighting performance in a space; the luminance distribution in the occupants' visual field; the color of the light perceived by the occupants. In spite of its importance for visual comfort, daylight discomfort glare is not so commonly addressed in the early stage design phases, because of the intrinsic complexity of the glare phenomenon, which has both a temporal and a spatial variation: it is a function of the user's position and direction of view and it is influenced by the dynamically changing luminance of the sky dome. Moreover it is influenced by material properties and geometrical aspects (i.e., window optical properties; presence, materials and geometry of moveable shading devices, etc.), which makes the evaluation of annual daylight glare even more complex [7].

A number of different glare indices was proposed in the past to quantify the discomfort glare potentially perceived by building occupants. Most of them were developed and validated for glare conditions caused by artificial light sources only. The first attempt to quantify glare from daylight is represented by the 'Daylight Glare Index' (DGI) [8], which had the merit to introduce in its equation all the main factors potentially concurring in the determination of a glare condition from daylight: luminance and solid angle of the source, average luminance of the background, position of the light source relative to the observer's field of view. However, even if it was later implemented [9], DGI showed a low reliability as a glare predictor in the presence of windows (especially large windows, constituting most of the observer's field of view, or when the sun is in the occupant field of view), as in fact, for most practical situations, the DGI showed to overestimate the glare condition actually described by the observers [10–13]. For a more general insight, a critical overview of the first glare indices is reported in [14].

To simplify the calculation of the daylight glare, attempts were made to estimate it by using the vertical illuminance at the eye level of the occupant, in replacement of the background luminance [15]. Osterhaus [16] assessed experimentally the subjective glare rating expressed by a sample of observers in the presence of large surfaces of non-uniform luminance (produced with electric lighting) and compared them to objective measurements of several glare indices, including DGI and eye vertical illuminance. In this study DGI showed the weakest correlation with subjective glare rating, while the vertical illuminance at the observer's eye showed the best correlation.

Following up an approach based on vertical illuminance, Wienold and Christoffersen [17] more recently introduced a new index, the Daylight Glare Probability (DGP), which expresses the percent of occupants disturbed by a daylighting glare situation. The index was validated by the same authors against a thorough set of experimental measures in real office rooms. Conceptually, the DGP accounts for luminance of daylight glare sources as well as for the vertical illuminance at eye level. This new method was implemented in the lighting calculation engine Radiance [18], through the purposely-developed tool Evalglare [19]. The calculation of DGP requires a High Dynamic Range (HDR) image (a photography or an image generated through a simulation) and a long computation time (especially for an annual glare analysis) to process luminances/illuminances in the scene with respect to one or more positions and directions of observations [20]. Moreover, a study by Pierson et al. [21] highlighted how a superficial understanding of the input data for Evalglare may lead to an inappropriate detection of glare sources, which in turn may determine an inaccurate estimation of glare indices. Since its introduction, the DGP has been adopted in several research studies to perform point-in-time or annual glare analyses, also in the presence of moveable shading or complex fenestrations systems [22–26].

At the same time, the evaluation of daylighting in buildings has moved towards the so-called Climate-Based Daylight Modeling (CBDM) [27,28], which considers annual dynamic daylight conditions (both sunlight and skylight), rather than limiting the analyses to single scenarios (i.e., overcast skies). The DGP is inherently a CBDM metric, as it depends on the sky luminance distribution, nevertheless, an annual DGP analysis is far time consuming, as it requires an HDR image to be generated for each time-step (typically an hour) considered during the course of a year. Furthermore, the DGP is dependent on the position and direction of view of the evaluation, which means that the calculation should be repeated for all relevant points in the space.

Different approaches to allow faster annual glare analyses were proposed in the past. Among the most relevant ones, two simplified methods were introduced by one of the authors of the DGP. The first one is the 'enhanced simplified Daylight Glare Probability', in which a simplified image is rendered for every considered time-step of the year, thus reducing the computational effort. This image accounts for the luminance of the main glare sources alone, without considering the exact luminance distribution within the room [29]. This solution allows a significant reduction in the computation time, as light inter-reflections are not accounted, but may present an underestimation problem in the presence of materials with a low visual transmission, translucent materials or materials that scatter the transmitted or reflected light. The enhanced simplified DGP proved to have a good correlation with DGP, therefore it was implemented in Radiance to allow faster annual glare simulations. The second simplified method introduced by Wienold is the 'DGPs' [30], which was conceived with the aim of excluding the luminance contrast component from the glare evaluation, hence further reducing the computational effort required. As a result, the DGPs is calculated from the eye vertical illuminance, which was correlated to DGP through a linear equation. Despite the DGPs allows faster annual evaluations (as it does not require an image to be generated for each time-step), it showed a good correlation with the DGP only for conditions when direct sunlight or highlight reflections are not present in the scene.

A further attempt to simplify the calculation of the daylight glare was carried out by Kleindeinst et al. and by Gagne et al. [31–33], who developed a simplified methodology (the 'model-based DGP approximation method' - DGPm), that uses luminance sources only for contrast evaluations through low-render images for a limited but representative set of 56 time-steps throughout a year. When compared to the DGP, as calculated using the Evalglare program in Radiance, the DGPm showed a correspondence within a 10% error over 90% of the time [31]. Moreover, the DGPm also allows spatial glare assessments to be carried out for a grid of points inside a space. The algorithm to generate the DGPm was implemented in Lightsolve [34]. A more in-detail review of indexes to evaluate discomfort glare can be found in [35].

Besides the attempts to develop methods for simpler but reliable glare analyses, some metrics were introduced to assess the risk of discomfort due to over-lighting in the frame of the CBDM approach. They are based on the annual workplane illuminance, which gives several advantages in terms of computation time. Two metrics estimate the percentage of occupied time for which a potential glare condition, corresponding to global illuminance over a threshold value, occurs in a point ('Maximum Daylight Autonomy' - DA_{max} [28] and 'Useful Daylight Illuminance exceeded' - $UDI_{exceeded}$ [36,37]), while a third metric, the 'Annual Sunlight Exposure' (ASE) considers the percentage of space with a direct illuminance from the sun over a threshold value (1000 lux) for more than a certain amount of time (250 h) over the year [38]. A review on the CBDM metrics that were proposed can be found in [39].

Following a different approach, Torres et al. [40] compared through a parametric study four illuminance-based metrics to the DGP: horizontal illuminance, vertical illuminance, vertical illuminance vector, and cylindrical illuminance. Through a fault-detection analysis, they found a correlation of each metric to the DGP in terms of capability of detecting or not a glare/non-glare condition. Based on the results, they proposed the use of the cylindrical illuminance as an accurate alternative metric to the DGP, with the advantage of retaining the vertical component of illuminance, while being view independent. A somewhat similar research, focused on studying a relation between the UDI and the DGP, was carried out by Mardaljevic et al. [41].

Within this framework, this paper introduces a simplified approach aiming at the classification of an entire space in daylight glare comfort classes, for a whole year, in a computationally efficient way. To speed up the calculation, the evaluation of the daylight glare condition is based only on the vertical illuminance at the eye level. Furthermore, daylight glare is evaluated not through the exact DGP value, but in terms of daylight glare comfort classes, as defined by Wienold in [29]: imperceptible, perceptible, disturbing, intolerable glare. Similarly to the approach used by Torres et al. [40] a fault-detection analysis was used to correlate the vertical illuminances to the daylight glare comfort classes, which correspond to specific ranges of DGP values. The approach was tested for an indoor space with different orientations, to which different glazing types and shading systems were applied.

A preliminary study was published by the same Authors in [42], where the methodology was tested on a limited number of case studies. The present work expands this earlier study, introducing a second orientation (west-facing spaces), different glazing properties and a comparison between the performance of the glazing and of two types of operable internal shading devices. The main goal of this paper is to present the simplified approach developed for an annual glare analyses and to critically discuss its potentials and drawbacks. Furthermore, in order to show the obtainable results, an explanatory application is presented.

2. Method and Case Study

The simplified approach presented in this paper aims at a spatial annual evaluation of the daylight glare comfort classes within a space, with a reduced computation time compared to a comprehensive and accurate annual glare assessment through the Daylight Glare Probability (DGP). The DGP [17], currently the most validated and widespread metric used to assess glare from daylight [39], is calculated according to the following equation:

$$\mathrm{DGP} = 5.87 \cdot 10^{-5} \mathrm{E_v} + 9.18 \cdot 10^{-2} \log\left(1 + \sum_i \frac{\mathrm{L_{s,i}^2}\,\omega_{\mathrm{s,i}}}{\mathrm{E_v^{1.87}}\,\mathrm{P_i^2}}\right) + 0.16 \tag{1}$$

where $\mathrm{E_v}$ is the vertical illuminance at eye level [lx]; $\mathrm{L_s}$ is the light source luminance [cd/m^2], ω_s is the light source solid angle [sr]; P is the position index [-], which expresses the variation in glare sensation experienced relative to the angular displacement of the light source from the observer's line of sight. The equation consists of two terms: the first one considers the vertical eye illuminance (mainly due to direct solar radiation), while the second accounts for the contrast between the scene background luminance and the luminance of the light sources within one's visual field. The computation of the second term is the most time-consuming, as the luminance contrast assessment requires an image to be created for the evaluation. On the contrary, the $\mathrm{E_v}$ assessment is a much faster and easier calculation. For an annual evaluation of the DGP in a position of the space considered, the tool Radiance can be used or, alternatively, a set of Radiance-based software, such as DAYSIM [43] or DIVA-for-Rhino [44].

The DGP range of variation is subdivided in sub-ranges linked with different glare sensations. The idea of associating glare indices to classes of glare sensation comes from Hopkinson, who first defined four classes: *Just Perceptible*, *Just Acceptable*, *Just Uncomfortable* and *Just Intolerable* [45]. This approach was adopted by Wienold, in accordance to the methodology described in [46] for thermal comfort rating, when defining his daylight glare comfort classes by correlating different glare sensations to specific ranges of DGP values [29]. Wienold's objective was to introduce a scale to rate visual discomfort for daylighting, in which each category is defined according to the user's satisfaction to be within each DGP threshold for at least 95% of time during a whole year (a possible exceedance of DGP thresholds for 5% of time is still allowed). For each daylight glare comfort class, a DGP threshold value was therefore defined, based on the analysis of an extensive set of numerical case studies. Table 1 summarizes all the daylight glare comfort classes with the relative DGP threshold values.

Table 1. Daylight glare comfort classes and relative DGP thresholds [29].

Daylight Glare Comfort Class	DGP Threshold
Imperceptible glare	DGP < 35%
Perceptible glare	35% ≤ DGP < 40%
Disturbing glare	40% ≤ DGP < 45%
Intolerable glare	DGP ≥ 45%

As outlined earlier, one of the drawbacks of the DGP is the computational effort needed to perform evaluations which are not limited to one point and one direction in space and to a single time-step, so that a spatial and multi-directional annual glare evaluation would be extremely computationally expensive.

The present paper presents a simplified approach which enables to classify a whole space in terms of daylight glare comfort classes by means of the eye vertical luminance E_v alone, without considering the luminance of the light sources and the luminance contrast in one's field of view. This results in a significant reduction of the computation time required, although it could introduce some errors in the assessment of the daylight glare comfort classes, as the contribution of the luminance contrast to glare sensation is neglected. This reduction in computational time can support: (i) a higher spatial and directional resolution of glare comfort assessment of the considered space; (ii) the adoption of more cost-effective measurements and sensors for controlling the considered space to minimize glare discomfort. In order not to compromise the accuracy in the estimation of the daylight glare comfort class, the evaluation and minimization of the errors introduced by the simplified approach presented hereby is of foremost importance. The simplified approach consists of the following steps, which will be discussed in detail in the following sections:

1. Step 1: Calculation of E_v thresholds to classify each viewpoint/direction of observation of a custom-defined grid in a certain daylight glare comfort class (corresponding to each DGP threshold value). This is done by means of a fault-detection technique;
2. Step 2: Quantification of errors from adopting E_v to classify a certain point in a daylight glare comfort class, compared to the exact DGP values, for each point of the custom-sized grid. The errors are expressed as underestimation and overestimation occurrences of the various glare conditions;
3. Step 3: Identification of the most suitable point in the space for the calculation of the E_v thresholds. These are adopted to classify the whole space according to the daylight glare comfort classes. This is done by identifying the point minimizing the errors quantified in Step 2.

Unlike the DGPs method [30], the presented approach aims at classifying a certain space into daylight glare comfort classes, rather than calculating the exact DGP for a certain point/direction of observation. Moreover, it is worth noticing that the accuracy of this simplified approach also depends on factors such as shape, size and orientation of the space considered, direction of the viewpoint in respect to the daylight source (window), geometric and optical properties of windows and of solar shadings. The present paper is a first evaluation of the suitability of the simplified approach, which was applied, as first exploration, to a case-study as described in the next section.

2.1. Application of the Simplified Approach to a Case Study

The simplified approach was tested for an enclosed office that is 3.6 m large, 4.5 m deep and 2.7 m high, with a window of 3.3 m width by 1.5 m height within one of the short walls. The case-study office is located in Turin (45.06° N, 7.68° E) and is alternatively oriented so as to have the window facing south and west. Table 2 summarizes the optical properties of the internal surfaces of the space.

Table 2. Optical properties of the materials used for the office selected as a case-study.

Surface	Visible Reflectance (R_v)
Floor	35%
Walls	65%
Ceiling	80%
External ground	10%

The investigated window configurations consisted of glazing with different transmission properties (specular or scattering) and different visible transmittances (T_v), for a total number of 14 glazing types. The scattering glazing was considered to be perfectly diffusing, i.e., the entire transmitted light is scattered in a uniform way towards the interior of the space. Table 3 summarizes all the glazing types and visible transmittances considered. The range of window optical properties is slightly different between specular and scattering glazing: this choice was made to match the realistic optical properties of commercially available technologies.

Table 3. Glazing types considered in the present study.

Parameter	Specular Glazing								Scattering Glazing					
T_v	3%	12%	15%	23%	34%	45%	55%	66%	6%	12%	15%	23%	34%	45%

Additionally to glazing characterized by different properties, also shading devices were considered, specifically venetian blinds with different slat angles and roller blinds with different T_v values, as summarized in Table 4. Venetian blinds were considered to have a slat depth of 3.5 cm, modeled as a plastic material with R_v of 44%. Roller blinds were modeled as a perfectly diffusing translucent material. Two different roller blinds were considered, one aiming at glare control, with T_v = 4%, and one aiming at solar control, with T_v = 15%., according to the typical light transmission values of commercially available products. All the shading devices were applied to the clearest specular glazing investigated (T_v = 66%).

Table 4. Shading devices considered in the present study.

Parameter	Venetian Blinds (VB)			Parameter	Roller Blinds (RB)	
Slat angle	0°	30°	60°	T_v	4%	15%

Three points in the room were identified to be representative of the different glare conditions occurring throughout the space analyzed. The three points were located at a height of 1.2 m above the floor, i.e., the height of the eyes of a seated person. For all the points, the direction of observation was assumed to be perpendicular to the window, in order to evaluate the glare for an unfavorable scenario. Figure 1 shows the location and direction of observation of the three points considered within the office space.

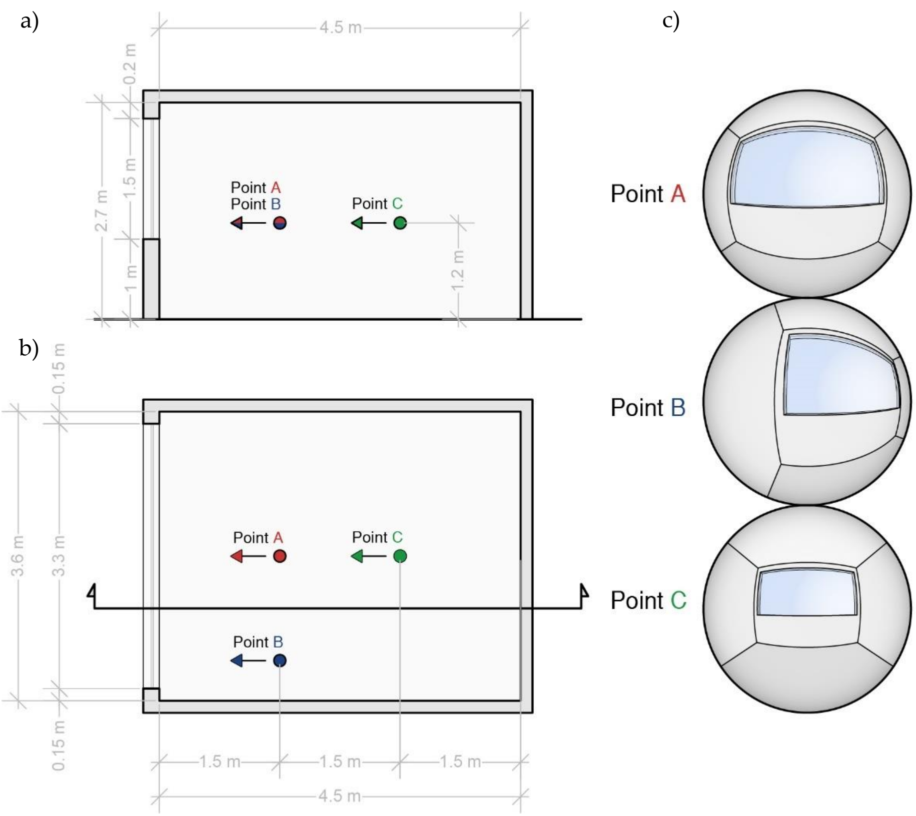

Figure 1. (**a**) Office section view, (**b**) office plan view, with the location and direction of observation of the three points considered; (**c**) fisheye view from the three different viewpoints.

DGP and E_v values for each of the three points were calculated, by means of DAYSIM software, for a whole year. To calculate annual DGP profiles DAYSIM uses the enhanced simplified DGP method described in [29], for which DGP is still evaluated through Equation (1), but the second term of the equation, i.e., luminance contrast, is calculated analyzing a simplified image (less time-consuming), in which the main scene luminance sources only are accounted. The following simulation parameters were chosen: ab = 5, ad = 1024, as = 128, ar = 300, aa = 0.1. The simulations were performed with a time-step of 1 h and only the moments in which daylight was present were considered, for a total amount of 4602 h (the number of annual daylight hours in Turin). This operation was repeated for every glazing type and shading device considered (see Tables 3 and 4), as well as for both orientations. The simulation outcome was an annual database for each glazing type and shading device, containing for each moment of the year a pair of values for each of the three points: a DGP value and an E_v value.

These results were post-processed, according to the 3 steps of the simplified method, which are described in detail in the following sub-sections.

2.2. Step 1: E_v Determination of the E_v Thresholds

The first step is aimed at defining the most suitable E_v values to be used as thresholds for each daylight glare comfort class (see Table 1). As four daylight glare comfort classes are identified, three E_v thresholds need to be calculated, similarly to the DGP thresholds: the lower threshold (corresponding to DGP = 35%; the intermediate threshold, corresponding to DGP = 40%; the upper threshold, corresponding to DGP = 45%).

The two E_v—DGP values determined for each time-step were used to evaluate the occurrence of glare (glare/non glare condition), using the DGP thresholds (DGP_{thr}) for each daylight glare comfort class as a validation reference. The most suitable values of E_v to be used as thresholds ($E_{v,thr}$) for the daylight glare comfort classes were found through the application of a fault-detection technique. In principle, comparing E_v to DGP_{thr}, to determine the best $E_{v,thr}$ value, may yield either one of the following four different scenarios:

- True Positive (TP): when $E_v > E_{v,thr}$ and $DGP > DGP_{thr}$;
- True Negative (TN): when $E_v < E_{v,thr}$ and $DGP < DGP_{thr}$;
- False Positive (FP): when $E_v > E_{v,thr}$ and $DGP < DGP_{thr}$;
- False Negative (FN): when $E_v < E_{v,thr}$ and $DGP > DGP_{thr}$;

Figure 2 exemplifies the four scenarios that may occur when applying the fault-detection technique. The results that were obtained for the intermediate threshold DGP_{thr} = 40% are shown. Actually, Figure 2 shows the correlation of E_v with DGP values for a certain point. The threshold DGP_{thr} = 40%, shown as a horizontal line (disturbing glare as per [29]), identifies a corresponding E_v threshold (vertical line). These two lines divide the graph into four sectors containing a different number of data points. The error in the daylight glare comfort class estimation is represented by the percentage of data points within the FP and FN regions. The most suitable $E_{v,thr}$ value for each daylight glare comfort class can be therefore determined as the one minimizing the sum FP+FN.

While a TP and TN results are "True" estimation conditions, i.e., they represent a correct estimation of the daylight glare comfort class, the "False" estimations (errors) are represented by FP and FN scenarios, which show a discordance between the estimation of a glare/non glare condition made through E_v and by means of the DGP value. In more detail, for a False Positive scenario a glare condition is detected by means of the E_v threshold, which corresponds to an overestimation of glare (as no glare is actually detected through the DGP value). On the contrary, for a False Negative scenario an actual glare condition (measured by the DGP value) is not detected through the E_v, resulting in an underestimation of the glare sensation. Therefore, between the two "fault" scenarios, FN appears to be the most problematic one, as visual comfort perceived by the occupant may be worse than the one estimated.

This fault-detection technique was applied to all the yearly simulated cases, i.e., different glazing types and properties and different shading devices, for each point and each window orientation. The outcome of such an analysis is a triplet of $E_{v,thr}$ (one $E_{v,thr}$ for each daylight glare comfort class threshold) for each glazing type and shading device, for each of the three points in the space considered and for each window orientation. A total number of 114 $E_{v,thr}$ triplets was obtained (19 façade technologies × 3 points × 2 Orientations = 114 $E_{v,thr}$ triplets).

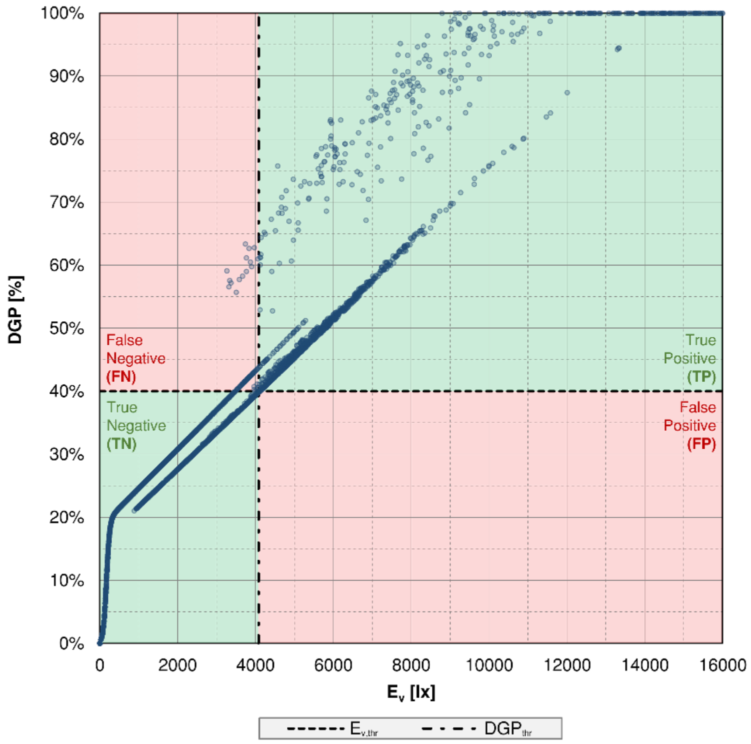

Figure 2. Example of the four scenarios occurring through a fault-detection technique to E_v and DGP values: green areas represent a correct estimation, while red areas represent an underestimation (FN) or overestimation (FP) of a daylight glare comfort class by means of E_v.

2.3. Step 2: Error Estimation

The second step of the approach consists in evaluating the magnitude of the error in the estimation of the daylight glare comfort class by means of the E_v threshold triplets, as compared to the correct DGP values. This can enable the classification of the entire space, in terms of daylight glare comfort classes, by means of the calculation of only one E_v triplet, and therefore by means of only one DGP annual calculation.

Firstly, $E_{v,thr}$ triplets obtained from the previous phase for each specific point are used to estimate the daylight glare comfort class for all the three points in the space (for each window characteristics and orientation). Secondly the resulting error, expressed as the percentage of occurrences of FP and FN over a year, is quantified for each point, for every case.

The result is a triplet of errors for each point considered (one error value for each daylight glare comfort class threshold), for a total number of 114 triplets of errors.

2.4. Step 3: Identification of Most Suitable Points for an Annual Glare Analysis

The aim of the last step is the identification of the most suitable point in the space, among the three considered, to be used to estimate the daylight glare comfort class for any point throughout the space considered. This can allow a space to be classified according to daylight glare comfort classes, by evaluating the annual DGP, and the relative $E_{v,thr}$ triplet, for one point only.

For each point (A, B, C), a point-specific average error was quantified for each of the three daylight glare comfort class thresholds. This one, expressed as the average percentage of FP+FN occurrences over a year, was calculated considering every glazing type and shading device, as well as both south and west orientations. Finally the most suitable point in the space was found as the one able to minimize the average error made when estimating the specific daylight glare comfort class by means of the $E_{v,thr}$ triplets calculated for that specific point.

3. Results

The results are presented with regard to each step of the approach. Finally, an explanatory example of this simplified approach is presented.

3.1. Step 1: Determination of E_v Thresholds

The $E_{v,thr}$ values for each daylight glare comfort class threshold are shown in Figure 3, these are relative to the different glazing types and shading devices, as well as for the different points in the space. As one would expect, for both window orientations $E_{v,thr}$ values relative to the lower daylight glare comfort class threshold are lower than those relative to the intermediate threshold, which are in turn lower than $E_{v,thr}$ values obtained for the upper threshold.

It is possible to observe that, for both south and west orientation, $E_{v,thr}$ values for some glazing types or shading devices are missing. This is true for all the three daylight glare comfort class thresholds, but especially for the upper one. The reason is that for these glazing types or shading devices the comfort class for which the threshold value is missing is never reached throughout the whole year. In fact, the technologies for which threshold values are missing are either glazing types or roller blinds with low T_v or venetian blinds with a high slat angle, i.e., technologies that allow a low amount of light inside the space. In these cases, higher daylight glare comfort classes, corresponding to worse glare conditions, are never experienced by the users, as these façade technologies prevent glare by blocking a high rate of the window incident light.

A common trend between the different daylight glare comfort class thresholds can be observed: $E_{v,thr}$ values tend to increase as the glazing or the shading devices allow a higher amount of light inside the room (glazing, both specular and scattering; roller blinds with higher T_v; venetian blinds with low slat angles). From another viewpoint, the lower the visible transmission of the glazing (either with specular or scattering properties), the more likely to perceive glare for lower eye illuminance levels.

For both specular and scattering glazing, beyond a certain T_v of the window, which varies depending on the daylight glare comfort class threshold, $E_{v,thr}$ values reach a plateau value (i.e., they fluctuate around an almost flat value). This $E_{v,thr}$ maximum value is instead never reached for the venetian blinds and the roller blinds, with the exception of the venetian blinds with a 0° slat angle, for which $E_{v,thr}$ close to the $E_{v,thr}$ maximum values are obtained. The maximum $E_{v,thr}$ values obtained for the south and west orientation are very close for each of the three daylight glare comfort class thresholds.

Comparing the outcomes relative to each of the three points in the space, it appears that higher differences in the $E_{v,thr}$ values for the three points can be observed for glazing and shading devices that allow a low amount of light within the room. As the quantity of light admitted to the internal space increases (higher T_v for specular and scattering glazing and for the roller blinds, lower slat angles for the venetian blinds) these differences tend to decrease. When the above mentioned $E_{v,thr}$ maximum value is reached, the differences between $E_{v,thr}$ relative to the three points are extremely low, practically negligible. This is particularly true for the lower threshold, while for the intermediate and upper thresholds small differences can still be observed, especially for the specular glazing. Generally speaking, $E_{v,thr}$ for point B is nearly always lower than $E_{v,thr}$ for point A, both for west and south orientation. As far as point C is concerned, instead, a different trend can be observed for the two orientations. For the west orientation, $E_{v,thr}$ values obtained for point C are nearly always lower than those obtained for point A and point B, while for the south orientation an exception to this trend can be highlighted for specular glazing with T_v of 12%, 15% and 23%, (the latter only for the upper threshold). In these cases the $E_{v,thr}$ maximum value is not reached, and $E_{v,thr}$ values relative to point C are significantly higher than those relative to point A and point B.

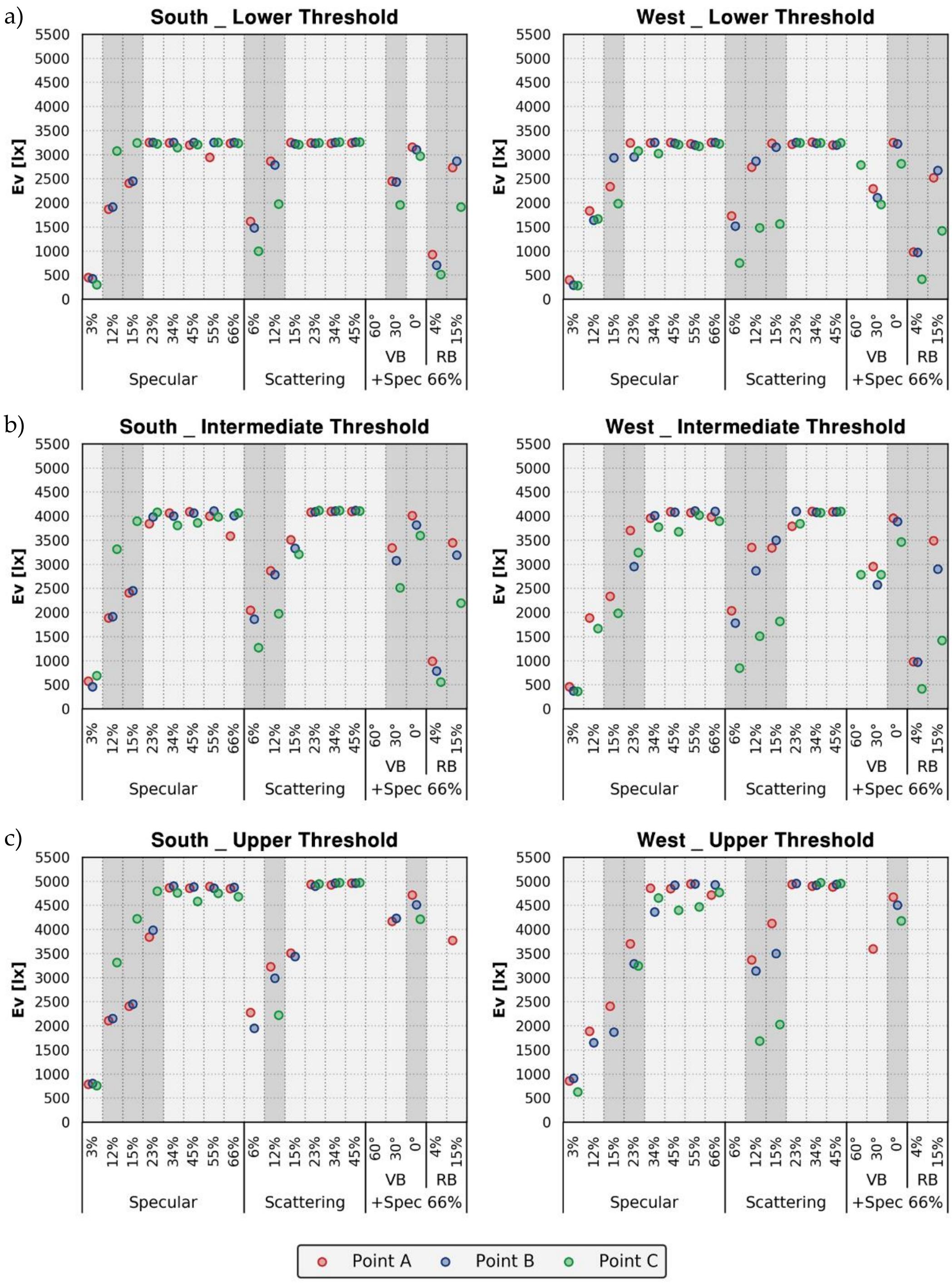

Figure 3. $E_{v,thr}$ values relative to every glazing type and shading device for: (**a**) lower threshold, south and west orientation; (**b**) intermediate threshold, south and west orientation; (**c**) upper threshold, south and west orientation. The darker gray bands highlight the cases where significant differences in $E_{v,thr}$ values were found for the three points considered.

Table 5 summarizes the minimum and maximum errors, for each orientation and daylight glare comfort class threshold, made when estimating a certain daylight glare comfort class by means of the different $E_{v,thr}$ (lower, intermediate and upper threshold). The errors are expressed in terms of FP+FN percentage, i.e., the percentage of time over the year in which each daylight glare comfort class is overestimated (FP) or underestimated (FN) by using the $E_{v,thr}$ values calculated.

Table 5. Minimum and maximum error, for each orientation and every daylight glare comfort class threshold, made when calculating all the $E_{v,thr}$. The errors are expressed as yearly percentage of occurrence of FP+FN.

Orientation	Error Relative to the Lower Threshold		Error Relative to the Intermediate Threshold		Error Relative to the Upper Threshold	
	min	**max**	**min**	**max**	**min**	**max**
South	0.33%	7.24%	0.02%	6.50%	0.02%	5.01%
West	0.11%	9.80%	0.02%	5.40%	0.53%	3.20%

It is possible to observe how, for each orientation, lower maximum errors were found for higher daylight glare comfort class thresholds. In more detail, the results show that the highest maximum errors are relative to the lower threshold, particularly for the west orientation. On the contrary, for the intermediate and upper thresholds, higher maximum errors were observed for the south orientation, compared to the west one. In any case, the highest maximum error was found to be lower than 10%.

3.2. Step 2: Error Estimation

This section presents the results relative to the step two of the approach, i.e., the calculation of the error made when spatially evaluating the daylight glare comfort classes. This was done by applying the triplet of $E_{v,thr}$ values calculated for each point in the space to all the three points considered for the glare analysis. The error is expressed in terms of percentage of occurrences over a whole year when each daylight glare comfort class was overestimated (FP) or underestimated (FN). The outcomes of this phase are summarized in Figure 4.

It is possible to observe that the errors relative to some glazing types or shading devices are missing, for both orientations. This happens as in the first step of the simplified approach it was not possible to calculate some $E_{v,thr}$ values, due to the fact that for some technologies a given daylight glare comfort class was never experienced by the user throughout the whole year. As a consequence, the errors relative to the cases with missing $E_{v,thr}$ values could not be calculated as well.

The results show how lower errors correspond to glazing with a higher T_v, for either specular or scattering glazing, that is to say glazing that admit more daylighting within the room. The same does not apply to the shading devices considered, neither venetian blinds nor roller blinds, for which instead a common trend is difficult to be defined.

Analyzing then the errors relative to each of the three points in the space, it is possible to observe how the errors for points A and B are in most cases very similar to each other. This does not apply to the errors for point C. In fact, for the west orientation it is possible to observe that for scattering glazing with low T_v, as well as for the roller blinds, the errors are significantly higher for point C than for the other two points. Moreover, the same trend, even though to a lower extent, was observed also for the venetian blinds, but only for the lower threshold. For the south orientation the same considerations apply, but in addition a small difference between the errors for the three points is present also for scattering glazing with low T_v.

Table 6 summarizes the minimum and maximum error made when evaluating each daylight glare comfort class by applying the $E_{v,thr}$ values calculated for each point in the space on all the three points considered. Again, the errors are expressed in terms of FP+FN percentage.

It is possible to observe that, both for points A and B, the maximum error is equal to approximately 5%. Furthermore, for both points a higher error is observed for the south orientation. The maximum error for point C is instead significantly higher (over 10% for both orientations).

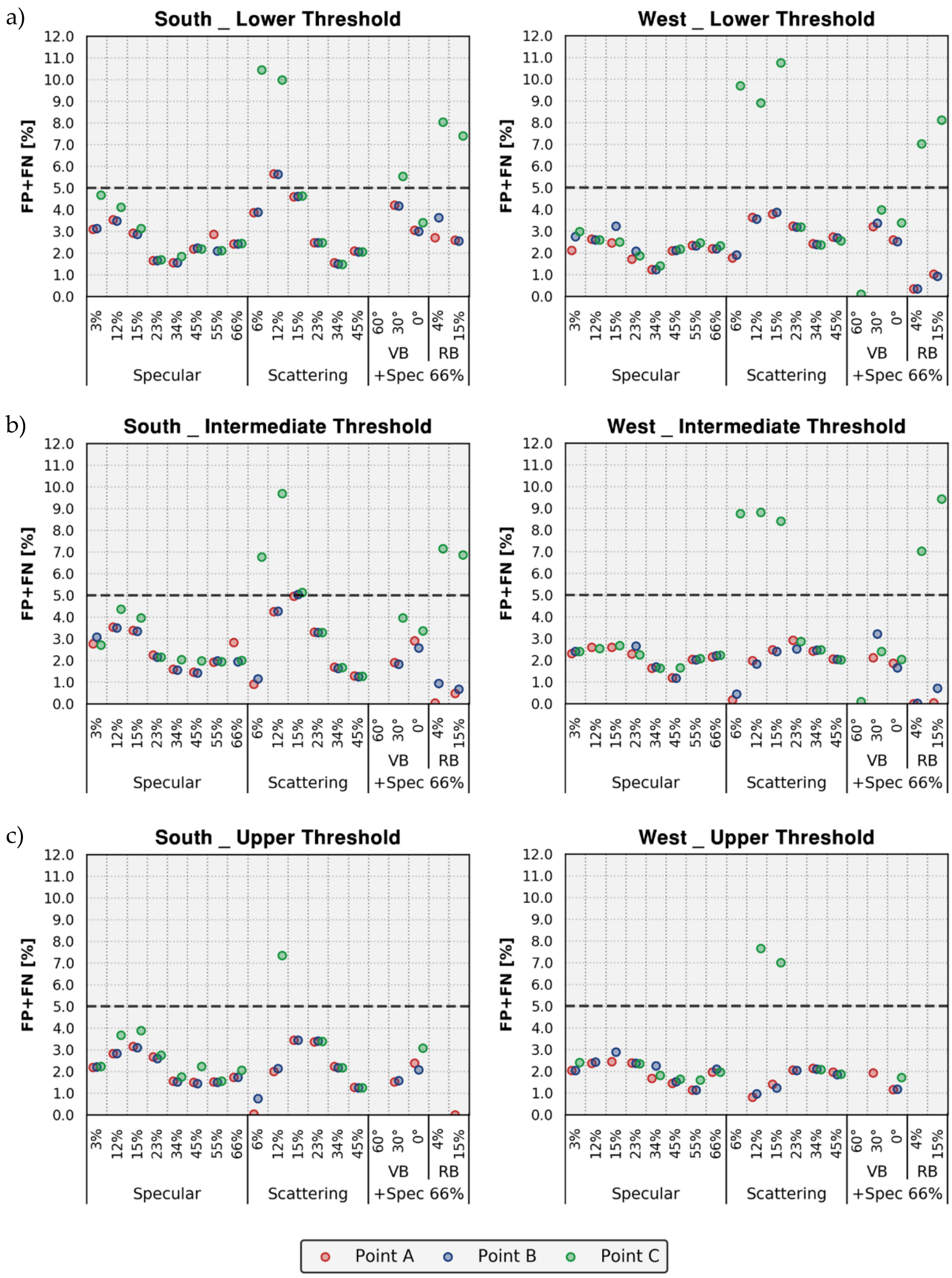

Figure 4. Error (in terms of percent occurrence of FP and FN over a year) relative to every glazing type and shading device considered for: (**a**) lower threshold, south and west orientation; (**b**) intermediate threshold, south and west orientation; (**c**) upper threshold, south and west orientation.

Table 6. Minimum and maximum error made when evaluating each daylight glare comfort class by applying the $E_{v,thr}$ values calculated for each point in the space on all the three points considered. The errors are expressed as FP+FN percentage.

Orientation	Errors for Point A		Errors for Point B		Errors for Point C	
	min	**max**	**min**	**max**	**min**	**max**
South	0.01%	5.66%	0.68%	5.64%	1.26%	10.44%
West	0.01%	3.79%	0.02%	3.87%	0.10%	10.75%

The errors presented so far are expressed as the percentage of FP and FN scenarios occurring over a year when estimating the daylight glare comfort class for the three points considered by means of the $E_{v,thr}$ calculated. But, as earlier outlined, between a False Positive and a False Negative estimation, the latter is certainly the most dangerous one, as this scenario negatively affects the evaluation of visual comfort of the occupants. In fact, for a yearly percentage of time comparable to the error estimated, a possible glare risk is not detected by means of this approach. For this reason it is worth analyzing also the maximum and minimum errors, in terms of percentage of FN alone, made when evaluating each daylight glare comfort class by applying the $E_{v,thr}$ values calculated for each point in the space on all the three points considered. The results of this analysis are summarized in Table 7.

Table 7. Minimum and maximum percentage of False Negative (FN) occurrences obtained, for each orientation and every daylight glare comfort class threshold, when evaluating each daylight glare comfort class by applying the $E_{v,thr}$ values calculated for each point in the space on all the three points considered.

Orientation	Point A		Point B		Point C	
	min	max	min	max	min	max
South	0.00%	4.79%	0.02%	4.50%	0.00%	4.40%
West	0.00%	3.78%	0.00%	3.68%	0.00%	3.17%

The results show how the values relative to FP alone are similar to those relative to FP+FN both for point A and point B, for both orientations. Instead, for point C the maximum error, in terms of FP, is significantly lower than that calculated as FP+FN, for both orientations. This means that for the cases with a high error for point C (in terms of FP+FN), i.e., scattering glazing with low T_v, and roller blinds, a great part of the incorrect estimations of the daylight glare comfort class is represented by a glare overestimation (FP), i.e., a less dangerous condition than the glare underestimation.

3.3. Step 3: Identification of Most Suitable Points for Annual Glare Analyses

The aim of the last step of the simplified approach was to identify the most suitable point for the calculation of the only annual DGP profile, among the three points in the space. From this, an $E_{v,thr}$ value for each daylight glare comfort class should be defined, to be then used to estimate the daylight glare comfort class for every point in the space considered. This was done by calculating the average error, considering all the glazing types and shading devices, for both orientations, for each point and for every daylight glare comfort class threshold. The error is expressed in terms of mean percentage of times over the year for which FP and FN scenarios occur for each point. Figure 5 shows all the average errors, split in mean FP and mean FN, calculated for each point and each daylight glare comfort class threshold.

For each daylight glare comfort class, it is possible to observe that the highest total error is observed for point C. Points A and B show instead similar total error values, for all the three thresholds, with errors for point A always slightly lower than for point B. For all the three points, the highest total average error was found for the lower threshold while the lowest error for the upper threshold. It is important to highlight that all the errors calculated are below the 5% error threshold defined in [46] and adopted by Wienold [29] for the definition of the daylight glare comfort classes.

Analyzing then the average errors relative to the percentage of occurrences of the FN scenario alone, a completely different trend is observed. Point C shows the lowest errors among the three points, for each daylight glare comfort class threshold. Points A and B still show similar error values, but in this case the errors for point A are always slightly higher than for point B. Again, the highest average FP error was observed for the lower threshold, while the lowest error for the upper threshold, for all the three points considered.

From the results obtained it is possible to conclude that for each of the three thresholds the highest average total error is obtained for point C, but at the same time point C shows the lowest mean error relative to FN alone, i.e., the lowest average occurrence of glare underestimation. Point A instead shows the lowest average total error, for every daylight glare comfort class threshold, but at the same time it is the point for which the highest mean glare underestimation is observed. Even if the False Negative scenario is the most dangerous one, both FP and FN occurrences are to be considered errors when estimating the daylight glare comfort classes by means of eye vertical illuminances. It can therefore be concluded that the most suitable point for which the DGP annual profile should be calculated is point A, as it is the one for which the lowest total average error is obtained in every threshold. This annual DGP profile should then be used to define the $E_{v,thr}$ values to be used to estimate the daylight glare comfort classes throughout all the space considered.

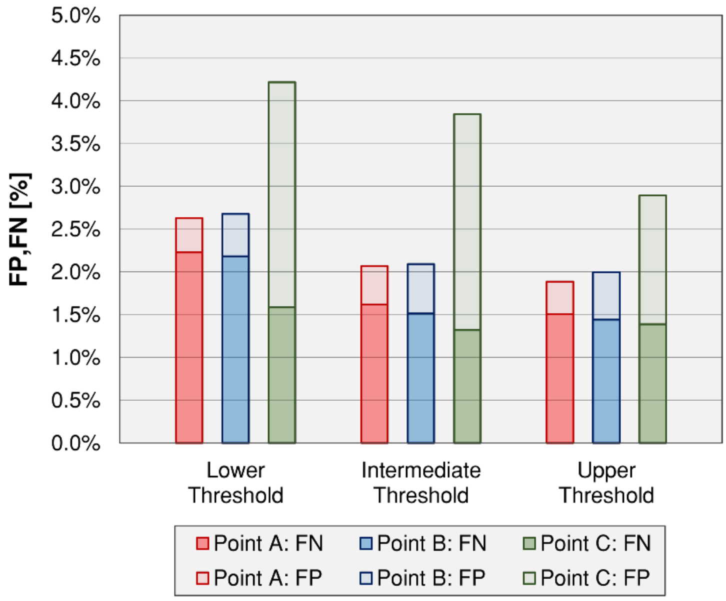

Figure 5. Average error for each point and for every daylight glare comfort class threshold. The average error is split between its two components, mean FP and mean FN.

3.4. Example of Application

In this section an example of the application of the presented simplified approach is provided. The case study used refers to the enclosed office considered in this study, west oriented, and with the window with scattering properties with a T_v equal to 34%. The eye vertical illuminance was calculated for a 7 × 5 grid of points, with a grid spacing of 0.5 m × 0.5 m, for a total number of 35 points across the room (deducting a peripheral stripe of 0.5 m). The points were located 1.2 m above the floor, with a direction of observation perpendicular to the window. A single annual DGP profile was calculated for the point A, which is shown in Figure 6. For this point, $E_{v,thr}$ values for each daylight glare comfort class were calculated by means of the fault-detection technique presented as the first step of the simplified approach. The following $E_{v,thr}$ values were estimated:

- Lower threshold: 3243 lx
- Intermediate threshold: 3957 lx
- Higher threshold: 4856 lx

By means of the above $E_{v,thr}$ values, the daylight glare comfort class for each of the 35 points in the room was estimated. Figure 6 shows the E_v values and relative daylight glare comfort class for the 35 points in the office for the 2nd of April at 17:00. This specific moment of the year was chosen as all the four daylight glare comfort classes appear to be experienced by the user for at least one point in the grid considered.

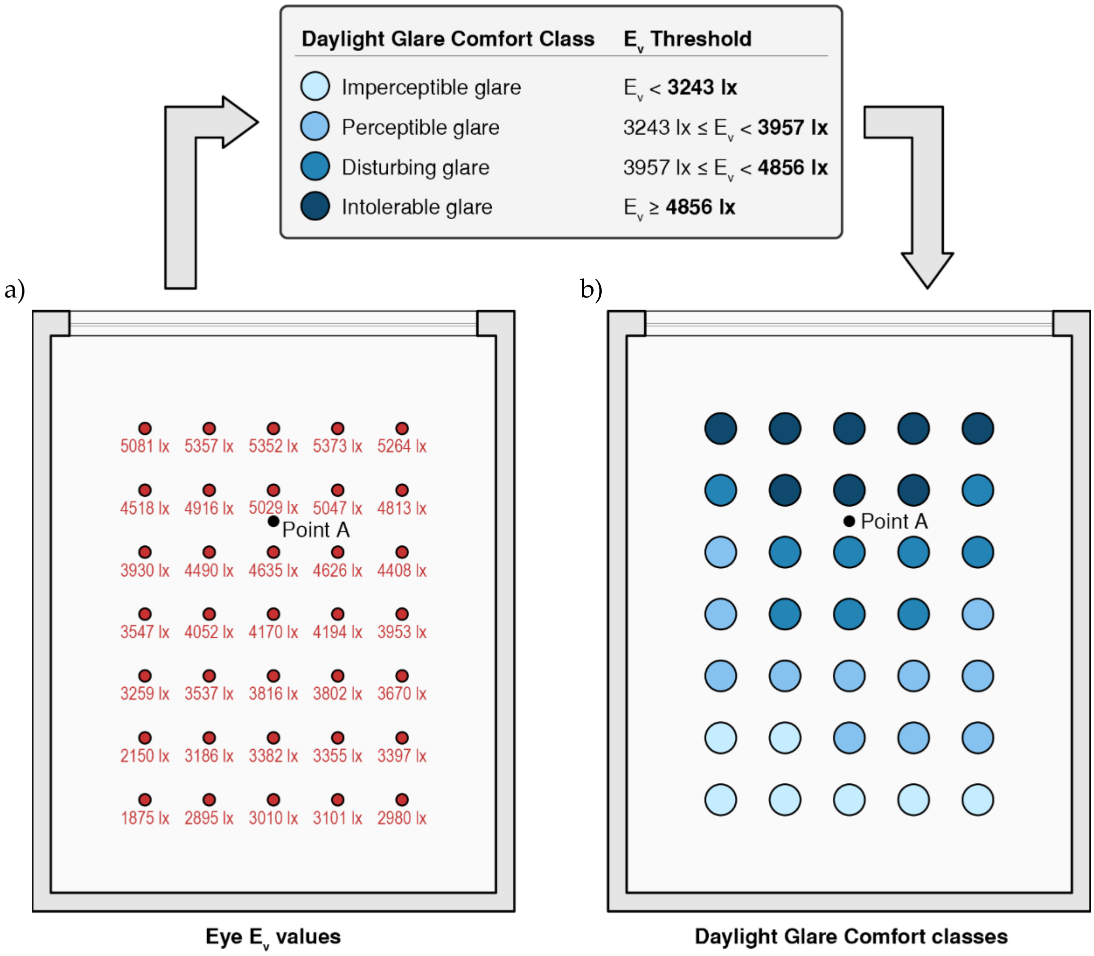

Figure 6. (**a**) Eye vertical illuminance values and (**b**) relative daylight glare comfort classes for the enclosed office case study with a west-facing window equipped with a scattering glazing with $T_V = 34\%$. Results for April 2nd, at 17:00.

Analyzing the outcomes obtained, the following considerations can be drawn:

- For 20.00% of the space (7 points) an *imperceptible glare* condition is experienced;
- For 31.43% of the space (11 points) a *perceptible glare* condition is experienced;
- For 25.71% of the space (9 points) a *disturbing glare* condition is experienced;
- For 22.86% of the space (8 points) an *intolerable glare* condition is experienced.

The spatial distribution of the daylight glare comfort classes shows, as one would expect, that a worse glare condition is perceived for the points closer to the window, while it improves as their distance from the window increases. The perception of the different daylight glare comfort classes appears in fact to vary in the space for stripes parallel to the window. For the front half of the room, the glare condition experienced by the user is that of intolerable glare or disturbing glare for nearly all the points, while for the back part the daylight glare comfort classes perceived are only those of perceptible glare and imperceptible glare. The analysis presented is performed for a single hour during the year, nonetheless it could be easily extended to evaluate the percentage of the space in a certain daylight glare comfort class throughout the whole year.

4. Discussion

The possibility of estimating daylight glare comfort classes by means of solely the eye vertical illuminance was explored. The most suitable $E_{v,thr}$ values (correlated to DGP values of 35%, 40%, and 45%) to classify a certain space according to daylight glare comfort classes were calculated for different glazing types and shading devices and for three different points within a sample enclosed office for a certain climate (Turin). This was done by means of the minimization of the error made when estimating each daylight glare comfort class for all the points in the room through the $E_{v,thr}$ calculated for each point, as compared to DGP values. This error, calculated as the average yearly sum of underestimation (FP) and overestimation (FN) of the daylight glare comfort class, was found to be below 5% for most of the cases analyzed. Such value is in line with the maximum error threshold defined in [46] and adopted by Wienold [29] for the definition of the DGP ranges for the daylight glare comfort classes. In fact in both works, comfort categories are defined according to the user satisfaction and within each category a 5% exceedance is allowed. This error limit of 5% is exceeded mainly for the analysis in point C, only in the presence of the scattering glazing with a low T_v (6%, 12% and 15%) and for the two types of roller blinds considered. While for the scattering glazing with T_v = 12% for the lower threshold, the 5% error threshold is exceeded also for point A and point B.

In general, it is worth noticing that all the cases that show an error higher than 5% are relative to technologies with a low T_v and scattering light transmission properties (both scattering glazing and roller blinds, which were modelled using a 'trans' material in Radiance). This means that the fault-detection technique used to determine the $E_{v,thr}$ values can be less reliable for technologies with low luminous transmittance values, and especially for the light diffusing ones, when the point considered is further than 1.5 m from the window (point C is 3 m far away).

By a closer look at the results, it can be easily understood that this is due to intrinsic simplifications of the presented approach, which only accounts for vertical illuminance at the observer eye, neglecting the contrast contribution to daylight glare. In the presence of diffusing window (or blind) materials (scattering technologies), the eye vertical illuminance is reduced while the area of the window with a higher luminance is enlarged, compared to the background luminance. For diffusing materials with a low T_v this effect is even amplified, as the ratio of the luminance of the source (the whole window) compared to light transmitted to the room is high. In the case of specular glazing with low light transmission the background luminance of the room is quite low, as well as the luminance of the window, except for the very high luminance of the light source within the window area (sun disk), even for windows with very low visible transmissions. In both cases a high luminance contrast between the light source luminance and the scene background luminance is perceived by the observer. As in the simplified method the luminance contrast is neglected, higher errors are found for glazing with a low T_v, both specular or scattering, compared to the errors relative to glazing with a higher T_v (for which the luminance contrast plays a negligible role). An example of such condition is presented in Figure 7, where the luminance map of the scene is shown, as seen from point C for the same time-step of the year (24 January at 14:30), for three different glazing. For Figure 7a, i.e., specular glazing with T_v = 66%, the estimation of the daylight glare comfort class by means of E_v is correct, as an eye E_v value higher than $E_{v,thr}$ and a corresponding DGP value higher than the DGP_{thr} are measured ($E_v > E_{v,thr}$ and analogously DGP > DGP_{thr}). For Figure 7b,c (same daylight conditions but considering a specular glazing with T_v = 3% and the scattering glazing with T_v = 6% respectively), the eye E_v fails at classifying the condition into the correct daylight glare comfort class. For the specular glazing (Figure 7b) the E_v is lower than $E_{v,thr}$ (corresponding to a DGP_{thr} of 0.45), while the real DGP value is higher than 0.45; for the scattering glazing (Figure 7c) the E_v is lower than $E_{v,thr}$ (corresponding to a DGP_{thr} of 0.35), while the real DGP value is higher than 0.35. In more detail, in Figure 7b the background luminance of the window is extremely low compared to the solar disk in the field of view of the observer (top right of the window), while in Figure 7c the window has a relatively high uniform luminance on its entire area (solar radiation diffused by the window), compared to the room background luminance.

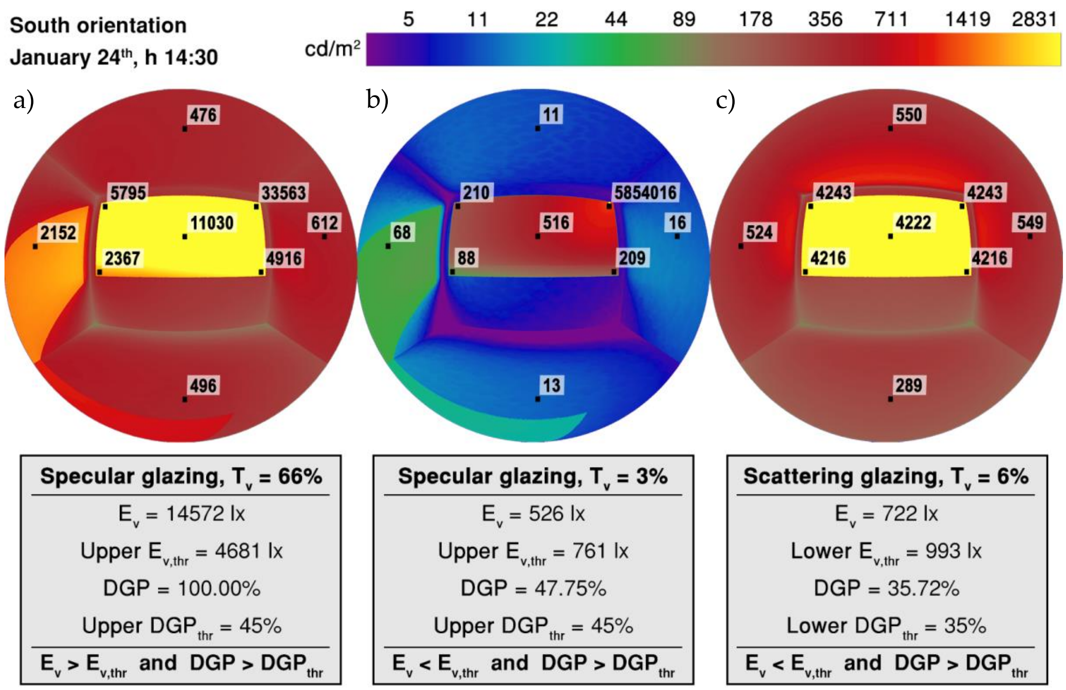

Figure 7. Luminance map of the observer's view field from point C, for: (**a**) specular glazing with T_v = 66%; (**b**) Specular glazing with T_v = 3%; (**c**) scattering glazing with T_v = 6%. All the luminance maps are relative to the 24 January at 14:30 and to south orientation.

In light of the above, the application of the simplified approach presented for glazing with low light transmission properties, either specular or scattering, may result in errors in classifying a space according to the daylight glare comfort classes. This can occur for a significant number of time-steps throughout the year, during building operations. Nevertheless, as calculated for the presented case studies, this error results in an underestimation of the glare risk (i.e., FN) for a percentage of time lower than 5%, for all the cases and all the daylight glare comfort class thresholds analyzed. Therefore, for the cases for which a total error (FP+FN) higher than 10% was found, a significant part of this is due to FP occurrences (overestimation of glare condition). Between these two classification errors, the underestimation of glare risk is certainly the most problematic, as it can lead to visual comfort conditions potentially worse than those estimated through this simplified approach. An overestimation of glare risk instead could actually result in lower glare risk than what estimated, even though this may lead to design or control choices towards a lower overall visible transmission of the window, potentially resulting in higher energy uses (higher artificial lighting and heating energy use, but potentially lower cooling energy use).

Among the three points considered, point A resulted as the most suitable to be used as a reference to define the $E_{v,thr}$ values to classify the whole space according to daylight glare comfort classes. In fact, point A resulted in average errors below 5% for each of the three daylight glare comfort class thresholds (average percentage of FP+FN), which can be considered acceptable (according to the definition of daylight glare comfort classes in [29]). Nonetheless, the impact of these errors on annual glare estimation may not be negligible, as they corresponds to a significant number of time-steps (number of hours during an annual analysis). Considering that in Turin there are 4602 daylight hours per year, these errors translate into the following amount of time in which glare is not correctly estimated:

- for the Lower threshold (imperceptible glare): average error of 2.63% = 121 h;
- for the Intermediate Threshold (perceptible glare): average error of 2.07% = 95 h;
- for the Upper Threshold (disturbing): average error of 1.89% = 87 h.

Despite the occurrence of these errors, as well as of their magnitude, it is important to highlight that this approach is aimed at providing a simplified and computationally efficient method to classify an entire space according to daylight glare comfort classes. As an example, considering the demonstration of application of the method provided in the *Results* section, to calculate the annual DGP profile for all the 35 points of the grid defined one would require a computation time 35 times higher compared to the presented approach: assuming to use an i7 processor (8 CPUs, 3.40 GHz), the evaluation of annual DGP for all the 35 points would require a time-machine of 17.5 h, against the 40 min needed for the whole space, with this simplified approach. Furthermore, the application of this method becomes even more convenient as the size of the space increases. Nevertheless, in presence of larger spaces, such as open-plan offices, a set of $E_{v,thr}$ triplets (instead of only one) may be necessary to classify the entire space in terms of daylight glare comfort classes, as the glare condition may substantially diverge in different areas within the same space. Although the determination of the minimum number of significant points (and their position) for which an $E_{v,thr}$ triplet should be calculated, is an open research point.

The present work investigated the potential of the simplified approach proposed on a limited data set (in terms of office geometry / size, orientation and latitude). Moreover the daylight comfort classes are evaluated by minimizing the total error in the estimation of the $E_{v,thr}$, although the False Positive (overestimation) or the False Negative (underestimations) may have a different influence on the visual comfort provided to the occupants or on the global energy performance of a space. Future study will explore the possibility of using $E_{v,thr}$ values defined minimizing different objective functions (FP, FN or FP+FN), depending on the aim of the analysis. Finally, it has to be noted that a spatial glare evaluation is currently possible only if the same direction of observation is considered for all the points on the custom-defined grid (this is the direction assumed for the DGP annual profile). Therefore, the approach proposed should most suitably be applied for a direction of observation representing the worst-case scenario within the space considered, so that for all the other directions of observation equal or better glare conditions are highly likely. The influence of the view direction in the accuracy in predicting daylight glare comfort classes by the present approach should be further studied as well.

The presented approach can be used to support decision making at an early design stage (when a large number of solutions need to be compared) and/or to support the design and implementation of real time control of façades with dynamic properties, aimed at reducing daylight glare risk. The main disadvantage of the approach lies in the fact that an estimation of the exact value of DGP is not possible, but the performance of the space (and of the selected façade technology and/or façade operation) is evaluated only in terms of daylight glare comfort classes.

5. Conclusions

The paper presents a simplified approach to classify a space according to daylight glare comfort classes, by means of vertical illuminances at eye level. DGP for a whole year is calculated for one point only and is then used as a valid reference to define the most suitable vertical illuminance threshold values for each daylight glare comfort class for that point. These thresholds are then used for all the other custom-defined points across the room (for which calculating the annual DGP is not necessary).

This simplified approach proved to be sufficiently accurate for the case study investigated, with a total average error for each daylight comfort class threshold below 3% for points A and B and below 5% for point C. The main advantages of this simplified approach are that (i) a spatial evaluation of the daylight glare comfort classes within a room is possible and that (ii) the computation time required for its application is significantly lower than that necessary for calculating DGP for the whole space. The main disadvantage is instead represented by its inability to estimate the exact DGP value, as only the daylight glare comfort class can be estimated for each point. However, this information could be useful enough to support decision making at an early design stage and building operation in a perspective of improving the control of glare conditions for the occupants.

The analyzed case study showed a good correlation between the daylight glare comfort classes estimated by means of the proposed approach and those deriving from the DGP evaluation. This is particularly true in the presence of glazing with a high value of T_v, for which the error estimated was always below 5%, while for less transparent technologies, i.e., glazing with a lower value of T_v and shading devices, an error higher than 5% was found in few cases.

The simplified approach was tested on a limited number of cases (i.e., in terms of room geometry, orientation and façade options), therefore future work will be aimed at: (i) evaluating the accuracy of the approach on larger spaces, different grid resolutions, directions of observation, façade options; (ii) testing the implication of adopting the presented approach on the design evaluation of alternative façade technologies and on the operations of dynamic façades.

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